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ENERGY BALANCE STUDIES IN CONIFEROUS FORESTS

by

L W GAY and J B STEWART

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L W Gay* and J B Stewart†

SUMMARY

A paper presented to the Swecon Seminar 1973 at Jadras, Ockelbo, Sweden, 14-20 May 1973. It considers the micro-environmental factors involved when radiation is transformed into other forms of energy at the surface of the earth with particular reference to the experience gained in two studies of the role of forest vegetation in the surface energy balance. These investigations are underway at Cedar River, near Seattle, Washington, USA and Thetford Forest, Norfolk, UK; both studies adopt a similar approach but experience different experimental conditions. This similarity in approach and instrumentation allows useful comparisons to be made from the results.

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1. INTRODUCTION

The key to a comprehensive description of the environment lies in a knowledge of the transformation and transfer of energy at or near the surface of the earth. Most of the energy transformations take place at the interface between the solid (or liquid) surface and the gaseous atmosphere. Solar radiation readily reaches the surface through the relatively transparent atmosphere. If the quantity of solar radiation is measured, the major problem remaining is to evaluate the rate at which it is transformed into other forms of energy.

The majority of these transformations involve forms of radiant, latent or sensible energy. The major effect of these transformations is the creation and maintenance of the general atmospheric circulation of the earth. The fraction that is photochemically fixed by plants, though small in quantity, has a significant effect upon man's activities.

The cycle of energy transformation at the earth-air interface is also associated with a corresponding cycle of mass. For example, the mass of water cycled at this interface can be readily expressed as energy required to effect its transformation from one phase to another. Likewise, the mass of carbon cycled between the biomass of vegetation and the atmosphere can be expressed as the equivalent energy required to change its phase from gas to solid in the photosynthesis process.

Transfer of energy and mass are governed by physical principles. Application of these principles in the past few decades has proved useful in studying such biological processes as growth and transpiration. It is not possible to define all of the physical, chemical and biological factors that affect living organisms, but we can identify certain physical factors that are exceedingly important in the energy and mass cycles. In doing so, we shall exclude factors pertaining to chemical composition of the soil and genetic characteristics of the organisms. The physical factors involved in the cycles of energy and mass between vegetated surfaces and the atmosphere are radiation, wind and precipitation, plus the temperature, moisture, and carbon content of the air, vegetation and soil. We shall follow de Vries (1963) noting that these factors may be on a macro-environmental scale, depending upon whether or not there is evidence of a marked surface influence, such as that derived from the type of vegetation, or the stage of its development. This paper will consider primarily micro-environmental factors in its discussion of energy transformations in coniferous forests. The major question to be considered is: how is radiation transformed into other forms of energy at the surface of the earth?

This leads to a concise statement of the objectives of this paper.

1. to review the importance of a physical theory of environment,
2. to discuss the application of such theory to vegetated areas,
3. to examine the results obtained from coniferous stands.

This will be done by reference to the experience gained in two studies of the role of forest vegetation in the surface energy balance. Both studies have used a similar approach, but under different experimental conditions.

2. LIST OF SYMBOLS

Symbol	Definition and Units
$A\downarrow$	atmospheric radiation flux, $W\ m^{-2}$
C	carbon dioxide concentration
C_i	volumetric heat capacity of air, biomass or soil, $J\ m^{-3}\ {}^oC^{-1}$
c_p	specific heat of air, $J\ kg^{-1}\ {}^oC^{-1}$
D	effective vegetation height, $D = d + z_o$, where the extrapolated wind profile becomes zero, m
d	zero plane displacement, m
E	water vapour flux, $kg\ m^{-2}\ s^{-1}$
e	vapour pressure, mb
e_s	saturation vapour pressure, mb
G	stored heat flux in air, biomass and soil, $W\ m^{-2}$
g	acceleration due to gravity, $9.81\ m\ s^{-1}$
H	sensible heat flux, $W\ m^{-2}$
h	height of trees, m
K_C	eddy diffusivity for carbon dioxide, $m^2\ s^{-1}$
K_E	eddy diffusivity for water vapour, $m^2\ s^{-1}$
K_H	eddy diffusivity for sensible heat, $m^2\ s^{-1}$
K_M	eddy diffusivity for momentum, $m^2\ s^{-1}$
$K\downarrow$	reflected global radiation flux, $W\ m^{-2}$
$K\uparrow$	reflected global radiation flux, $W\ m^{-2}$
K^*	net global radiation flux, $W\ m^{-2}$
k	Von Karman's constant, 0.41
$L\downarrow$	longwave radiation flux, incoming, $W\ m^{-2}$
$L\uparrow$	longwave radiation flux, outgoing, $W\ m^{-2}$
L^*	net longwave radiation flux, $W\ m^{-2}$
P	net photosynthetic energy flux, $W\ m^{-2}$
p	atmospheric pressure, mb
Q^*	net allwave radiation flux, $W\ m^{-2}$

q	specific humidity, g kg^{-1}
$q_w(\theta)$	saturation specific humidity at temperature θ, g kg^{-1}
R_i	Richardson number
T	temperature, ^oC or ^oK
t	time, s
r_a	aerodynamic resistance, s m^{-1}
r_s	surface resistance, s m^{-1}
u	windspeed, m s^{-1}
z	height above a reference plane, m
z_o	roughness length, m
α	coefficient in the stability correction function
β	Bowen ratio
γ	exponent in the stability correction function
Δ	an operator denoting a finite difference
ε	ratio of the mole weight of water to air, 0.622
θ	potential temperature, ^oC
λ	latent heat of vapourisation of water, J kg^{-1}
λE	latent heat flux, W m^{-2}
Λ	heat of assimilation of carbon, J kg^{-1}
ρ	density of air, Kg m^{-3}
ϕ	stability correction

3. FUNDAMENTALS OF ENERGY TRANSFER

The micro-environmental aspects of basic energy transfer have been reviewed in a number of other papers (Webb, 1965, Federer, 1970; Tajchman, 1971; and Stewart and Thom, 1973, among others) so derivations need not be repeated here. Certain basic equations, however, are summarized below as an aid in interpretation of results to be given later.

3.1 ENERGY BUDGET EQUATION

The energy budget equation is merely a statement of the principles of conservation of energy: the sum of energy fluxes across the boundaries of a system are equal to the amount of work done on the system. Let the system boundaries be a plane of infinite extent, positioned at the top of the vegetation. The major fluxes between vegetation and the atmosphere can then be indentified and summed in the widely used energy budget equation

$$Q^* + \lambda E + H + G + P = 0 \tag{1}$$

The first three terms represent fluxes across the reference plane which serves as the system boundary, Q^* is the net exchange of radiation, λE is the latent heat flux, and H is the sensible heat flux. The last two terms represent changes in energy within the system, ie., the volume beneath the boundary plane. G is the change in sensible heat stored within the air, biomass and soil, while P is the net transformation of energy by photosynthesis and respiration. The usual sign convention is adopted so that Q^*, λE and H are positive when their sense is directed downward, and G and P are positive when they represent energy leaving storage. Each of the components in equation (1) can be expressed in terms of the factor selected to represent the physical environment.

3.2 RADIATION EXCHANGE

Net radiation is the net exchange of radiation crossing the reference plane over all wavelengths. It can be represented as the sum of the shortwave (K) and longwave (L) fluxes.

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow = K^* + L^* \tag{2}$$

where the arrows indicate direction, and (*) signifies net exchange. Net radiation is also a measure of the net transformation of energy from radiant to non-radiant forms. Its measurement, therefore, represents the amount of energy that is partitioned into latent, sensible and chemical energy.

3.3 LATENT AND SENSIBLE ENERGY

The latent and sensible heat fluxes crossing the reference plane can be evaluated by a number of methods. Those considered here are based upon time-averaged, profile measurements of temperature, moisture concentration, and wind velocity.

Transfer Equations. Basic transfer equations represent the latent and sensible heat exchanges as being proportional to the respective gradients of specific humidity (approximated by $\Delta q/\Delta z$) and potential temperature ($\Delta\theta/\Delta z$)

$$\lambda E = -\rho\lambda K_E \Delta q/\Delta z \tag{3}$$

and

$$H = -\rho c_p K_H \Delta\theta/\Delta z \tag{4}$$

K_E and K_H are the diffusivity coefficients for vapour and for sensible heat, respectively.

The constants are defined in the symbols list.

Equations (3, 4) are not applied directly because the diffusivities are not known.

Bowen ratio. The Bowen ratio, β, is the ratio of the flux of sensible heat to that of latent heat. From equations (3) and (4)

$$\beta = \frac{H}{\lambda E} = \frac{c_p K_H \Delta\theta/\Delta z}{\lambda K_E \Delta q/\Delta z} \tag{5}$$

Since experimental evidence (Dyer, 1967) shows that eddy diffusivities are equal, equation (5) reduces to

$$\beta = \frac{c_p \Delta\theta}{\lambda \Delta q} \tag{6}$$

so that the Bowen ratio can be obtained from measurements of potential temperature and specific humidity at two heights. In practice, to reduce instrumental errors, it is preferable to obtain the gradients of potential temperature and specific humidity from profiles of these quantities measured at a number of heights. By combining equation(1) with the Bowen ratio, the latent and sensible heat flux can be obtained:

$$\lambda E = -\ (Q^* + G + P)\ /\ (1 + \beta) \tag{7}$$

$$\begin{aligned} H &= -\ (Q^* + G + P)\beta /\ (1 + \beta) \\ &= \lambda E \beta \end{aligned} \tag{8}$$

Aerodynamic Methods. The aerodynamic equations can be written in a variety of ways to express the fluxes in terms of the several factors (temperature or vapour concentration, windspeed) and height.

$$\lambda E = \rho \lambda k^2 (\Delta e \Delta u / (\Delta\{\ln(z-d)\})^2)\phi \tag{9}$$

and

$$H = \rho c_p k^2 (\Delta\theta \Delta u / (\Delta\{\ln(z-d)\})^2)\phi \tag{10}$$

Constants are defined in the symbols list.

The term ϕ is a correction for the effects of atmospheric stability near the surface. It represents the ratio of the transfer coefficient for heat (or vapour) to an analogous transfer coefficient for momentum, K_M. When the temperature stratification in the atmosphere is adiabatic, or neutral, the value of this ratio (and of ϕ) is unity. When a temperature gradient exists, however, the transfer of heat and water vapour will be enhanced in unstable (lapse) conditions and suppressed in stable (inversion) conditions when the ratio will depart from unity. A correction is provided by the model

$$\phi = (1 - \alpha Ri)^{\gamma} \tag{11}$$

where α and γ are constants and Ri is the Richardson number (Richardson 1920).

The Richardson number expresses the relative contributions to transfer of the buoyancy effects due to heating, and the frictional effects due to wind. It is approximated by

$$Ri = \frac{g\ (\Delta\theta/\Delta z)}{(273+\bar{\theta})(\Delta u/\Delta z)^2} \tag{12}$$

where $\bar{\theta}$ is the mean potential temperature of the air layer (and other constants are defined in the list on page 3).

The values of α and γ appear to be related to the heights of measurement and to the roughness of the exchanging surfaces, for which a range of values have been proposed. For example, one formulation (Paulson, 1970) suggests that α = 15 and γ = 0.75. The values suitable for forests are not yet determined, and the use of the aerodynamic method over forests is therefore not recommended at present.

3.4 STORED ENERGY

The flux of stored energy actually represents the quantity of sensible energy gained or lost from storage beneath the reference plane during the period of measurements. It can be expressed as

$$G = \sum_{i=1}^{m} C_i(\Delta T/2)_i \Delta z_i/\Delta t \tag{13}$$

where the distance beneath the reference plane has been divided into m layers, each with a volumetric heat capacity of C_i, a mean temperature change of $(\Delta T/2)_i$ and a thickness Δz_i. The time interval for the measurement of ΔT is Δt. Appropriate heat capacities and temperatures can be used to determine the storage changes in the air, biomass and soil beneath the reference plane.

Stewart and Thom (1973) approximated the total change in stored energy by the empirical equation

$$G = k_1\Delta T + k_2\Delta q \tag{14}$$

where ΔT and Δq are the respective hourly changes in temperature ($^{o}C\ hr^{-1}$)

and specific humidity (g $kg^{-1}hr^{-1}$) in the air layer between the reference plane and the ground. When G has units of Watts per square metre, $k_1 = 18$ and $k_2 = 17$.

Photosynthesis. The flux of photosynthesis energy is small, normally being a few per cent of Q*. The flux of photosynetic energy will be neglected here because of its small magnitude and because it was not measured in our studies.

If the gradient of CO2 ($\Delta C/\Delta z$) is measured, net photosynthesis can then be written as a transfer equation, similar to those (Eqns. 3, 4) established for sensible and latent energy:

$$P = -\rho\Lambda K_c \Delta C/\Delta z \tag{15}$$

With the assumption that the eddy diffusivity of CO_2 equals those for sensible and latent energy ($K_c = K_H = K_E$) the photsynthetic flux can be written into a Bowen ratio model (Eqns. 7, 8) as was done by Denmead (1969) or into an aerodynamic model analogous to Equations (9) and (10).

4. APPLICATION TO FORESTS

The basic energy transfer formulations have been thoroughly tested over areas that are bare, or else covered with low, relatively smooth vegetation. The results have been reported by many authors in the past decade. Application to forests, however, has revealed some problems that are associated with the size and scale of forest canopies.

4.1 SPECIAL CONSIDERATIONS

The mere height of forest vegetation can create mechanical difficulties in placing instruments. The support towers must be sturdy and safe to climb, yet they must not unduly disturb the environment. There are often practical problems in orientating instruments. It is also difficult to ensure that the properties temperature, humidity and windspeed are measured at the same effective level in the atmosphere. Psychrometers ordinarily measure T and e in the same air stream, but anemometers are necessarily placed some distance away. Tanner (1963) suggests graphical tests for checking the assumption that all three factors are indeed being measured at the same level.

In addition to these mechanical difficulties, the structure of the forest canopy creates problems that are not apparent in energy budget studies over low, dense vegetation. The leaves in coniferous canopies are relatively sparsely distributed over a considerable depth, providing a diffuse source of sensible and latent heat. Surface roughness further enhances mechanical mixing in the atmosphere near the canopy and as a result, the gradients of temperature and humidity are in the neighbourhood of a few hundredths (°C or mb) per metre. This is an order of magnitude lower than the gradients encountered over low, dense vegetation, and there is a corresponding increase in the difficulties of obtaining the required measurement precision.

The upward displacement (d) of the profile must also be determined for the application of the aerodynamic equations (9) and (10) to forests. Fortunately, the accuracy requirements for measurement of d become less stringent as the profiles are displaced to greater heights above the ground surface. Normally it is assumed that the same d applies equally to the profiles of temperature, humidity and windspeed. However, the sources and sinks of sensible and latent heat, and momentum, may well occur at different levels in the considerable depth of the diffuse coniferous canopy. This would require an appropriate displacement height be determined for each factor.

4.2 SITE REQUIREMENTS

The criteria for suitable sites appear to become more stringent as the height of the vegetation increases. The horizontal extent of an experimental site limits the maximum height at which the sensors can be placed. The minimum sensor height is affected by the uniformity and structure of the canopy.

The fetch, or distance over the vegetation surface under study through which the wind travels before reaching the sensors, must be sufficient to allow the development of an equilibrium layer in which the profiles of temperature, humidity and windspeed are affected primarily by the experimental surface. A long fetch effectively eliminates horizontal advection and assures that the fluxes are vertical. The relationship proposed in agricultural studies give ratios of fetch to maximum instrument height (presumably measured above the effective vegetation height, D) in the range of 100 - 500 to 1. If this relationship is extrapolated to forests, then a fetch of tens of kilometres appears to be needed. It is evident that the forest energy budget studies reported to date cannot meet such stringent fetch requirements. It seems likely that the profile equilibrium will be achieved more rapidly over a rough forest surface than over lower, smoother vegetation (Pasquill, 1972); such an effect would ease the fetch requirements considerably.

The uniformity and structure of the canopy affects the minimum height at which the sensors can be placed. The lowest sensor must be within the equilibrium layer and not be unduly influenced by local features of the canopy. Lettau's (1959) rule of thumb for smooth surfaces and low crops suggests that the lower sensor level should be at least five times the height of the average roughness element (z_0). Presumably, in tall vegetation the distance would be measured above the effective vegetation height, D. If typical forest values in the order of $z_0 = 0.1h$ and $D = 0.7h$ are to be used for illustration, the rule suggests a minimum instrument height of 1.2h over forests. Again, definitive estimates are lacking for tall, rough vegetation. The higher the instruments above the canopy, the smaller are the gradient quantities, and the more difficult it becomes to make the measurements.

4.3 CHARACTERISTICS OF TWO EXPERIMENTAL SITES

Energy balance studies are now underway at two coniferous forest sites that appear to approach the ideal specifications of a level, uniform forest of infinite extent. The intensive study site of the US Coniferous Forest Biome on the Cedar River, near Seattle, Washington, is predominantly second-growth Douglas-fir (*Pseudotsuga menziesii*). The Institute of Hydrology has centred its forest studies in a plantation of Scots and Corsican Pine (*Pinus sylvestris* and *nigra* var. *calabrica*) near Thetford, Norfolk.

Cedar River. The stand and soils characteristic at Cedar River have been described by Fritschen (1972). The Douglas-fir forest is about 35 years old and originated as natural regeneration following logging. The density averages 570 trees per hectare with an average spacing of about 5.7 m. The meteorological study site is on the broad, flat valley of the Cedar River. The soil is a Barneston, gravelly, loamy sand originating from a glacial outwash; the root system is restricted to the upper metre of soil. The mean dbh is about 16 cm and the average height of the stand is 28 m. The canopy is relatively level, with a uniform canopy density.

Thetford Forest. The site at Thetford is located in a plantation of Scots and Corsican pine that extends uniformly over 70 square kilometres of almost level land. There are about 870 trees per hectare on a sandy soil one to two metres deep overlying chalk. At the site of the meteorological experiments, the 40 year-old trees have an average height of 16 m and an average separation of about 3 m.

4.4 ENVIRONMENTAL INSTRUMENTATION

A number of environmental data acquisition systems have been described in recent years. Some of these systems have been mobile (Clayton and Merryman, 1960; Valli, 1966), but most have been fixed installations (Allen, 1970; Backlund and Perttu, 1971; Fritschen and Van Bavel, 1963; Reifsnyder, 1963). Fritschen (1970) has reviewed specific requirements for data systems employed in microclimate research. All of these systems have sought to combine the attributes of precision and convenience in application, with ease in data handling and processing.

The performance of these and similar systems has continued to improve with the development of new instruments and with increased experience in field operation. The major improvements have been in data collection and handling procedures, as digital data systems have now become common place for environmental studies. These systems can readily collect great quantities of data with a high degree of precision. The use of small on-line computers is just beginning to minimize the sometimes laborious, and often slow, data processing tasks associated with environmental studies.

The accuracy requirements for resolving very small gradients of T, e and u present the biggest problem in the design of an instrumentation system for forest energy budget studies. Two different approaches have been used at Cedar River and at Thetford. A discussion of the characteristics of these systems should be helpful for those planning to undertake similar studies elsewhere.

Cedar River Instrumentation. The system used at Cedar River was developed at Oregon State University for use in a variety of environmental studies. It has been described in detail by Gay (1973a Ch.2). The system includes a digital recorder, a truck-mounted laboratory, a power source, sensors, signal cables and instrument supports.

The digital recorder will scan up to 100 analog inputs at a rate of 5 per second with a resolution of 0.001 per cent (0.1 microvolts on a 10 millivolt scale). The recorder also contains a 12-channel digital scanner for recording the pulse output of anemometers (Gay and Holbo, 1970). The system output is on punched paper tape and printed strip. The system uses ceramic wick, thermocouple psychrometers of the basic design of Lourence and Pruitt (1969), modified by Gay (1973b) for measurement of temperature and vapour pressure gradients. Windspeed measurements are made with Thornthwaite cup anemometers that use a photochopper circuit to generate a pulse output. The shortwave radiation components were measured with Kipp pyranometers, and the allwave components with Lange pyrradiometers of Schultze's design. The deployment of the system at Cedar River in 1971 has been described by Gay (1972).

During the 1972 field season, a new instrument configuration was used. Six psychrometers and anemometers were mounted at 1 m intervals on a vertical support mast 6 m in length. The hollow, rectangular support mast served as a common aspiration duct for the psychrometers, which were ventilated by a single fan mounted at the lower end. This instrument package was suspended above the forest, and held approximately 4 m away from the tubular, triangular TV antenna tower which was 0.3 m in width and 37 m high. The instrument packages were orientated with respect to the up- and down-valley winds that prevailed at this site. The suspended package could be raised or lowered with an electric winch for servicing as desired.

Instrument packages were suspended from each of two towers located about 100 m apart. Pyranometers and pyrradiometers were mounted on a boom extending 3 m away from the south face of each tower at the 36 m level. Soil heat flux discs and soil temperatures were measured near the base of each tower. In addition, the temperature and humidity of the air was measured at ground level (1 m) with two psychrometers near one of the towers. All sensors were sequentially recorded at intervals of five minutes during the day, and 10 minutes at night. The system was in operation at Cedar River for 6 days in 1971 and for 20 days in 1972. The observations took place at the end of July and in early August during both years.

The US Coniferous Biome project is sponsoring a variety of inter-related studies at the Cedar River site. These involve ecologists, physiologists, soil scientists, hydrologists and meteorologists. Close co-operation exists between the work described here and the energy budget investigations of Dr Leo Fritschen, College of Forest Resources, University of

Washington, Seattle. Energy budget model testing is being carried out in conjuction with Dr Fritschen's lysimeter installation (Fritschen 1972) and his eddy flux system which began operation late in 1972.

Thetford Forest Instrumentation. The instrumentation system developed by the Institute of Hydrology for use at Thetford differs from the more conventional approaches that have been referred to on page 4. The basic temperature system employs quartz crystal thermometers, while data handling is facilitated with the use of a small, on-line computer. Additional details of the system are given by Stewart (1971), Oliver (1971) and Oliver and Oliver (1973).

The arrangements during the 1971 field season were given by Stewart and Thom (1973). Profiles of temperature and humidity were obtained from wet- and dry-bulb temperatures measured by aspirated quartz crystal thermometers. Each wet-bulb consists of a water-filled ceramic tube which encloses the thermometer, similar to the system described by Lourence and Pruitt (1969). The thermometers, previously inter-calibrated to $\pm 0.01^{\circ}C$, are mounted in radiation shields at six heights above and three heights within the forest canopy. Two sets of instruments facing in opposite directions are used and data from the upwind side are selected for temperature analysis. The sampling rate is once per minute for each thermometer.

Wind profiles were measured with sensitive photoelectric anemometers fitted with light-weight (six-cup) polystyrene rotors. The anemometers are mounted at six levels above and five levels beneath the top of the canopy. They have been inter-calibrated in a wind tunnel to an accuracy of ±1 per cent. Wind run is totalized for each hour.

Incoming and reflected solar radiation and net radiation were measured every 15 seconds with sets of instruments mounted at a height of 4.7 m above the canopy on east and west facing booms, the set with the better exposure being used in each analysis. When both sets of instruments were equally well exposed, measurements from the two CSIRO net radiometers, which which were 10 m apart in 1971, agreed to within 4 per cent.

All instrumental output is fed into a computer-controlled data acquisition system. The computer simplifies the crude data, calculates the time averages and records the results on punched paper tape. Hourly average values are printed out for efficient monitoring and easy initial analysis.

In 1972 the instrumentation at the site was improved by the installation of two more towers to support additional Kipp pyranometers and the net pyrradiometers. A plotter was added to the computerized data system so that the performance of the psychrometers and anemometers can be monitored more efficiently by inspection of the hourly average profiles of temperature, humidity and windspeed. The system operated for a total of 66 days in 1971, 45 days in 1972 and 54 days in 1973.

The Thetford measurements have been co-ordinated with a continuing study of soil moisture by the Subsurface Section of the Institute of Hydrology and with an evaluation of the physiological characteristics of the trees under the direction of Professor A J Rutter, Botany Department, Imperial College, London. During the spring observations in 1973, the British Meteorological Office carried out a series of eddy flux measurements as a first step towards comparing forest energy budget estimates made by two independent methods.

5. RESULTS

The physical theory described in the preceding sections has been applied to the Cedar River and the Thetford forest sites. The similarity of approach and of instrumentation at each site enhances the usefulness of comparisons that can be made from the results. Two clear summer days are compared, in order to tabulate the energy exchange characteristics that were found at these two dissimilar locations, and to provide a means for evaluating the role played by the characteristics of the forest vegetation at the two sites.

5.1 ENERGY EXCHANGE CHARACTERISTICS

Clear warm weather conditions occurred on 10 August 1972, at Cedar River, latitude 44^{o} and 7 July 1971 at Thetford, latitude 52^{o}. The respective mean temperatures at the top of the canopy were 15^{o} and 17^{o}. Comparisons will first be made of the radiation exchange at the two sites, and then the energy budget components will be discussed.

Radiation Exchange. The radiation totals for the two days are tabulated in Table 1. The values reveal that both sites received similar inputs of solar radiation (K↓). The Douglas-fir forest reflected 9.1 per cent of the incident solar radiation, an amount slightly greater than the 8.1 per cent value measured at Thetford. The net radiation at Cedar River was about 85 per cent of that measured at Thetford. The reasons for this will be examined further.

Table 1. Radiation exchange above the canopy at the Cedar River and Thetford sites. (MJ m^{-2})

1MJ m^{-2} = 0.44 mm water equivalent

	Q*	K↓	K↑	L↓	L↑
Cedar River	16.75	25.95	2.44	27.72	34.48
Thetford	19.73	27.73	2.26	29.31	35.05

The downward longwave component (L↓) at Cedar River was obtained by subtraction of the measured downward short- and allwave components; L↑

was then obtained by substitution in Equation (2). The longwave components at Thetford were obtained by solution of Equation (2), after L↑ had been estimated as the blackbody radiation emitted at the absolute temperature of the canopy. The Thetford canopy temperature was approximated as (T_a + 2°K) in the daytime, and (T_a - 1°K) at night, where T_a was the air temperature measured at the tops of the crowns. Our other measurements suggest that this gives a suitable approximation of emitted longwave radiation.

The diurnal course of the radiation components is shown in Figure 1. The curves are drawn by eye through hourly average values. The symmetry confirms that cloudless skies prevailed for the duration of the measurements. The dotted lines are extrapolations through an afternoon data gap that occurred at each site.

The total allwave energy incident upon the canopy (K↓ + L↓) was 53.69 MJ m^{-2} at Thetford. The difference is to a large part attributed to the longer day period at Thetford. At Cedar River, 36.92 MJ m^{-2} were returned to the atmosphere from the canopy (K↑ + L↑), so that the net radiation, or amount of radiation converted to non-radiant forms, was 16.75 MJ m^{-2}. The corresponding amounts at Thetford were 3.37 MJ m^{-2}. The differences in radiation exchange do not appear associated with the slightly smaller albedo at Thetford; this effect could provide only an additional 0.27 MJ m^{-2} to the Thetford canopy. Thus the Thetford forest appeared somewhat more effective than Cedar River in partitioning the absorbed radiant energy into sensible and latent energy, and into storage. The nature of the partition can only be understood by examination of the energy budget components for the two experimental days.

Components of the Energy Budget. The energy budget was evaluated at each site, using the Bowen ratio method (Equations 7 and 8). The daily totals are tabulated in Table 2, and the diurnal course of the fluxes is plotted in Figure 2.

Table 2. Energy budget components at the Cedar River and Thetford sites (MJ m^{-2})

IMJ m^{-2} = 0.40 mm water equivalent

	Q*	G	λE	H
Cedar River	16.75	0.21	-9.99	-6.96
Thetford	19.73	-0.98	-7.00	-11.75

The net radiation at each site was converted into somewhat different forms of energy. At Cedar River, a small amount (0.21 MJ m^{-2}) of sensible energy came out of storage over the day, while the Thetford estimates show that a small amount (-0.98 MJ m^{-2}) went into storage. Latent energy was appreciably larger at Cedar River than at Thetford

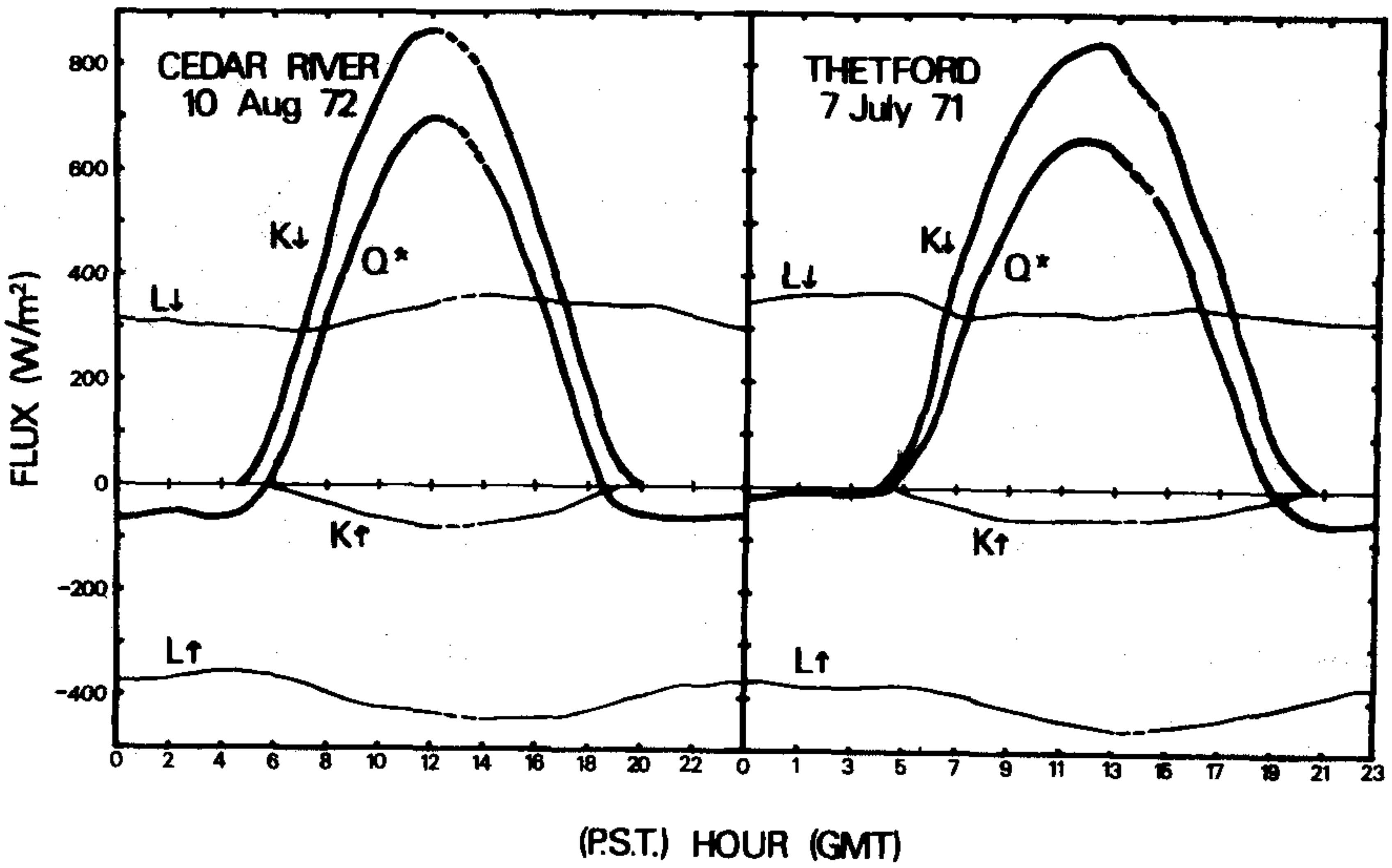

Figure 1 Components of the radiation balance for Cedar River, Oregon, USA, latitude 44°, and Thetford Forest, Suffolk, UK, latitude 52°

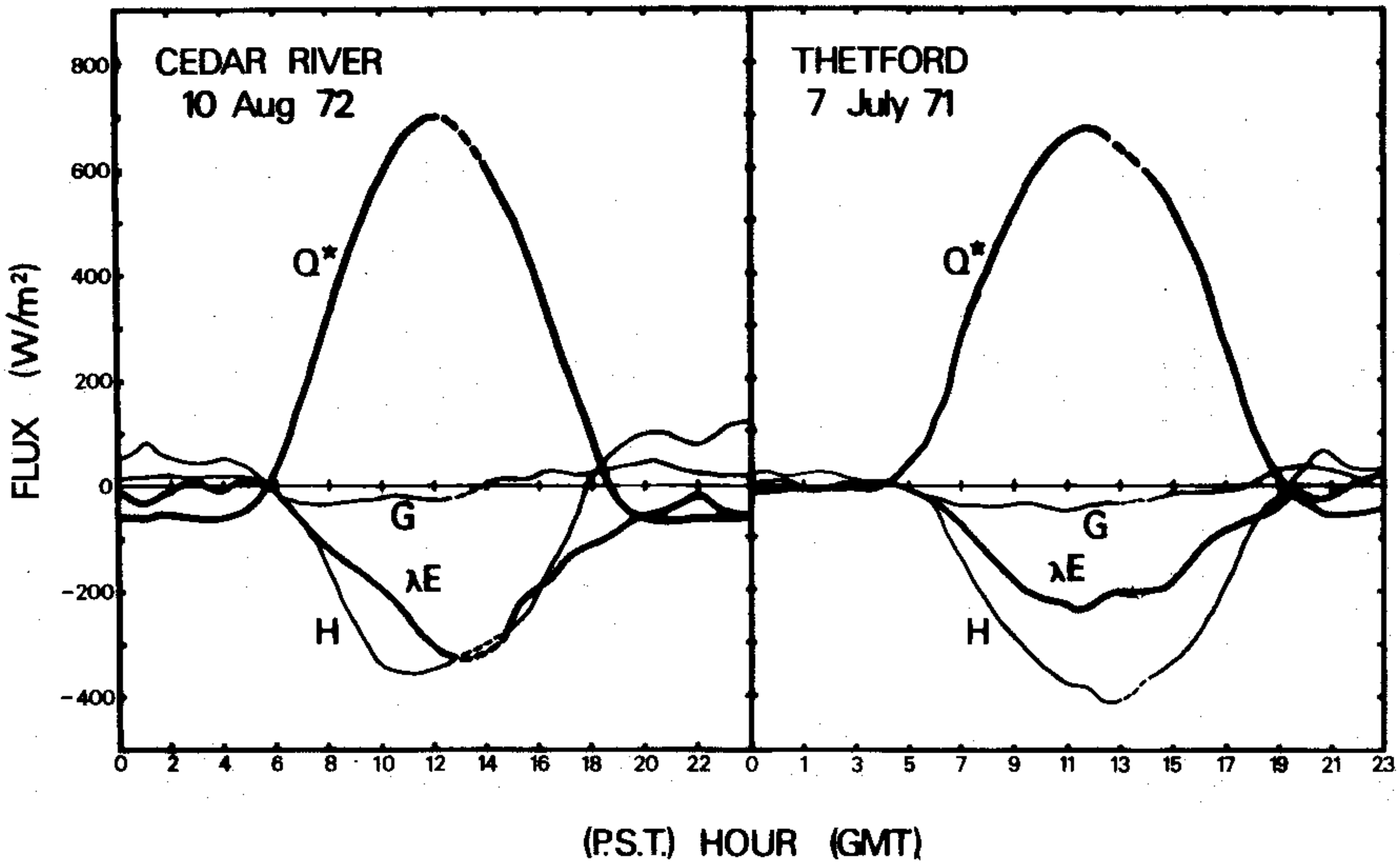

Figure 2 Energy budget components for Cedar River, Oregon, USA, and Thetford Forest, Suffolk, UK

The 9.99 MJ m^{-2} vapourized at the Douglas-fir site is equivalent to about 4 mm of water, as compared to 7.00 MJ m^{-2} and 2.8 mm water equivalent at Thetford.

The mean daily Bowen ratio ($H/\lambda E$) was 0.7 at Cedar River, and 1.68 at Thetford. However, comparison of day-long values can often give a distorted impression, unless the relative day lengths are considered in relation to the input of radiant energy at the site.

The diurnal course of the energy budget components (Figure 2) shows similarities between net radiation and the storage flux at the two sites. The net radiation curve at Thetford suggests that it was cloudy during the morning hours before sunrise. The early morning values at Cedar River, and the late evening values at both sites are in keeping with the steady net radiation loss of about -60 W m^{-2} that normally prevails under clear skies. The storage curve is also similar at both sites, as it shows a maximum rate of perhaps -40 W m^{-2} within a few hours after sunrise, changes over from sink to source in the mid-afternoon, and then continues as a steady source during the hours after sundown. The daily changes in storage are quite small at both sites but the hourly figures do become large enough to affect the available energy in the morning and evening.

Not only are the magnitudes of the sensible and latent energy fluxes different at the two sites but the phase relationship differs as well. The Douglas-fir forest at Cedar River appears to partition more energy into sensible heat in the morning, and more into latent energy in the afternoon. In contrast, the sensible and latent fluxes are in phase agreement throughout the day at Thetford.

A similar relationship between sensible and latent energy was observed at the same Douglas-fir site in 1971 (Gay, 1972) and over a Douglas-fir forest in British Columbia by McNaughton and Black (1973). The effect may be related to physiological characteristics of the two species; the possible causes will be discussed further in a subsequent section.

Notes on the Analysis. The Bowen ratio method used in this analysis is sensitive to small offsets in the various instruments used to measure the profile values of T and e. The small gradients of T and e intensify this problem. A graphical technique (Gay, 1972) was used to select a suitable pair of levels from the Cedar River data. In contrast, a statistical procedure is used at Thetford to determine the best estimate of the Bowen ratio, based upon measurements at all levels above the canopy. In either case, measurements from a number of levels are needed.

Aerodynamic analyses over forests have not generally given results comparable to the Bowen ratio analysis. The effective vegetation height, d, was estimated to be 21 m (0.75h) for Cedar River and 12 m (0.76h) for Thetford. The roughness lengths ranged from 2 to 6 m at Cedar River, and averaged 0.93 m (0.06h) at Thetford. Wind profile analyses of 1970 data from Thetford have been discussed by Oliver (1971).

5.2 PLANT FACTORS

Progress in relating micrometeorological observations to stand characteristics has been based upon improved understanding of the processes controlling transfer between individual leaves and their environment. At this small scale, the concept of stomatal resistance has been helpful in examining mass transfer to and from the leaf surface, while boundary layer resistances are known to control the transfer of mass, sensible energy, and momentum between the leaf surface and the environment. On a larger scale, the canopy is an assemblage of individual leaves; surface resistance (r_s), analogous to stomatal resistance, governs the exchange of mass, sensible energy and momentum between vegetation and the atmosphere (Monteith, 1965). Aerodynamic resistance (r_a) is similar in concept to the boundary layer resistance of individual leaves; it expresses the atmospheric resistance to the transfer of mass, sensible energy and momentum within the lower layer of the atmosphere. The aerodynamic resistance to transfer varies somewhat, depending upon the entity being transferred, but this need not concern us here.

Stewart and Thom (1973), have reviewed surface resistance theory, and have applied the concept to forests. Their derivations will not be repeated here. We shall instead examine the results of the two experimental days with respect to the energy budget analyses presented in the preceding section.

The surface resistance and the aerodynamic resistance are plotted in Figure 3, for the daylight period of measurement at the two sites. At both sites, surface resistances are low during the morning (r_s<100 s m^{-1} with a general increase in the afternoon. This trend is consistent with other clear days analysed at Thetford. The surface resistance values at Cedar River, however, are generally about half of the values that prevailed at Thetford throughout the day.

The r_s values provide an indirect indication of the stomatal resistance of the canopy. A detailed analysis of the series of Thetford measurements (Stewart and Thom, 1973) revealed average forenoon values of r_s to be about 115 s m^{-1}. This indicates that the average stomatal resistance of individual needles in the canopy will be about 1200 to 1300 s m^{-1} a value that compares well with porometer readings made on individual needles at the site. Supplementary resistance measurements are not available for Cedar River.

The aerodynamic resistance for momentum exchange, r_a, is given in Figure 3. The Cedar River values are relatively high in the early morning hours, when the wind patterns are dominated by light, down-canyon winds. The r_a values at the two sites are virtually the same during the afternoon period, when the winds at Cedar River are dominated by stronger up-canyon flow. The Cedar River velocities remain rather low (<2 m s^{-1}) even during the afternoon, measured at 3 m above the canopy. The Thetford values at the same height were generally greater than 3 m s^{-1} throughout the day.

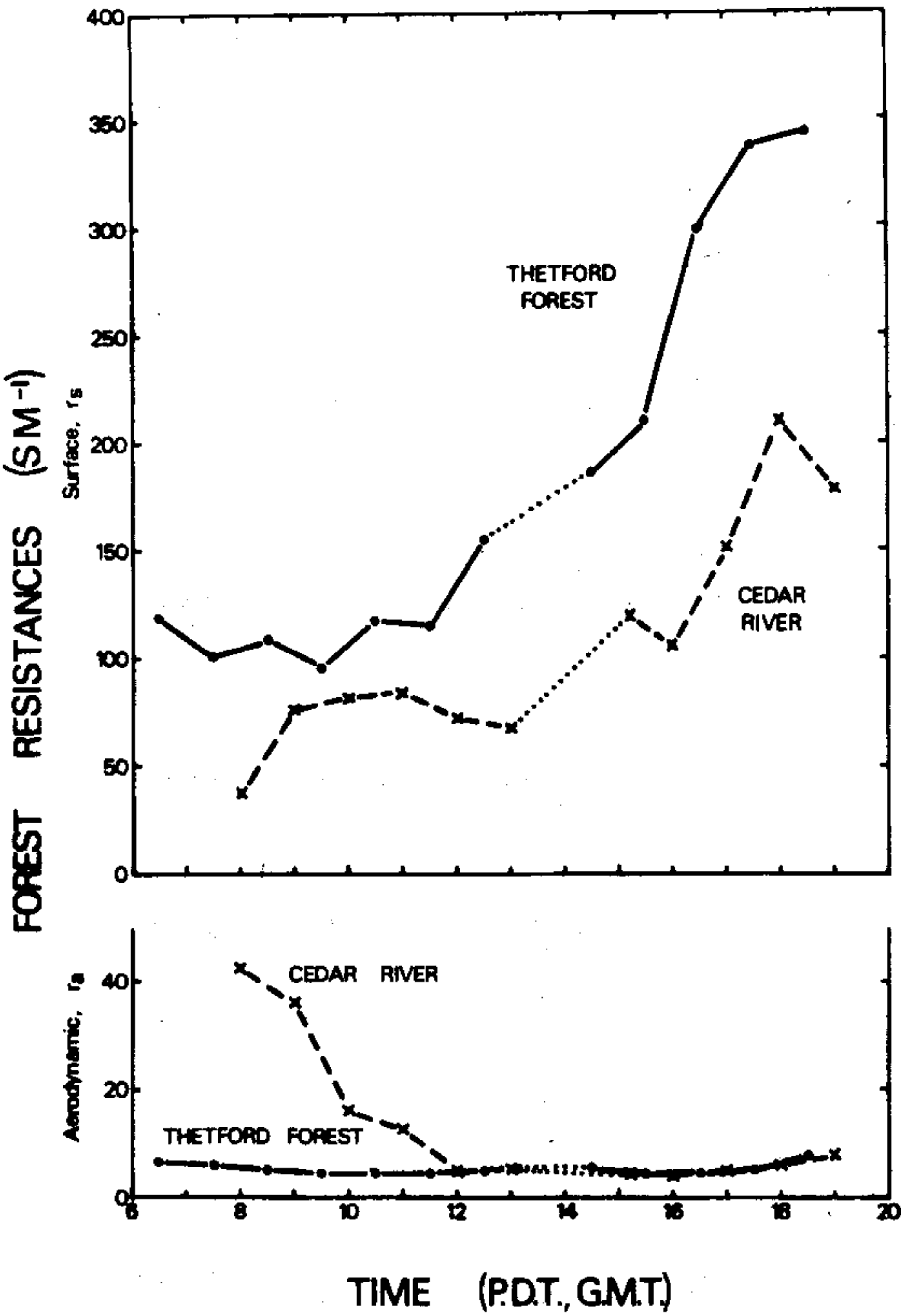

Figure 3 The variation of aerodynamic and surface resistance of Thetford Forest on 7 July 1971 and of Cedar River on 10 August 1972.

Surface and aerodynamic resistances have been reported for only a few forest sites. This is partly because the concept is rather new, and partly because wind measurements are needed for the analysis, in addition to the temperature and vapour measurements that are normally made for the Bowen ratio method. Szeicz, Endrodi and Tajchman (1969) calculated resistances in their analysis of Tajchman's measurements over spruce near Munich. Their forest values of r_s generally ranged from 100 to 150 s m^{-1}; these were about 2 or 3 times larger than values over lucerne and potatoes. Values of r_a were in the order of 3 s m^{-1} over the spruce forest.

The two resistances act in series to restrict transfer between the vegetation and the atmosphere. The computation of the diurnal trend of surface values from micrometeorological measurements is particularly useful in demonstrating the biological component of the control of transpiration. This control is much more effective in forests than in low vegetation because of the very small aerodynamic resistance of forests. As an illustration based upon typical values, an increase in surface resistance of a forest by a factor of two will reduce the evaporation by a factor of nearly ½ whereas for short grass the same increase in surface resistance will only affect the evaporation by a factor of $^1/_5$, or less. The resistances can also shift the phase of the λE & H fluxes: λE is known to be proportional to the vapour pressure deficit of the air, which increases in the afternoon on clear days of the type considered in our examples. An increase in stomatal resistance, which increases the surface resistance, can compensate for the increased evaporation potential and thus keep the λE curve in phase with H and Q*. This is the pattern that has been observed at Thetford. However, the observations over the Douglas-fir forest at Cedar River show that the peak in the latent heat flux is about one hour after the peak in the available energy and is more nearly in phase with the specific humidity deficit. This is the result of the smaller diurnal change in surface resistance observed at Cedar River than at Thetford. Thus the surface resistance of the Douglas firs increased by a factor of 1.4 from mid-morning to mid-afternoon, whereas that of the pines increased by a factor of 1.9 over the same time. McMaughton and Black (1973) have made measurements of latent heat flux over a Douglas-fir forest in British Columbia. They found that the peak of latent heat flux was about two hours after the peak in available energy. Their values of surface resistance, estimated using assumed profiles of wind velocity, show similar change - by a factor of 1.5 from mid-morning to mid-afternoon.

6. SUMMARY AND CONCLUSIONS

The energy budget method has proved useful in studying a variety of environmental problems. However, there are difficulties involved in transferring to forests the techniques that have been successful for crops and other low vegetation. Not only are the measurement problems considerably more complex, but it also appears that aerodynamic models may not be applicable to surfaces as rough and fiberous as coniferous canopies.

Application of energy budget theory to forests of Douglas-fir and of Scots pine revealed differences in the way absorbed radiant energy is transformed. There were similarities, however, in the radiation budgets of the two sites for the cloudless, midsummer conditions studied. Tabulation of the energy budget components showed that the Douglas-fir forest transformed a 60 per cent of its net radiation into latent energy as opposed to 36 per cent for the Scots pine.

An examination of the transfer resistances at the two sites revealed that the Douglas-fir had surface resistance values in the neighbourhood of 50 to 200 s m^{-1}, while the Scots pine values were in the range of 100 to 400 s m^{-1}. The diurnal trends in the resistance values can explain the apparent tendency for latent energy to be enhanced during the afternoon hours over Douglas-fir forests, while the greater diurnal trend observed over Thetford Forest caused the latent flux to be in phase with the available energy.

Although the results discussed here provide a basis for initial comparison of the energy transfer characteristics of two dissimilar forest communities, it is recognized that the response depends upon the physiological processes as well as upon physical factors. Some of these points can be reconciled through examination of resistances to transfer. However, analysis and interpretation of energy balance studies must ultimately include measurements of the physiological state of the forest as well as measurements of the physical state of the atmosphere.

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